Astron. Astrophys. 151, 131–136 (1985)

ASTRONOMY
AND
ASTROPHYSICS

Two-epoch observations of the core radio structure in extended quasars

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Received April 11, accepted April 24, 1985

Summary. VLBI maps of the parsec scale structure in the cores of several large extended radio sources associated with quasars have been obtained at two epochs. The position angle of the small and the large scale emission are found to be in good agreement. Two-sided nuclear jets are detected as well as an upper limit of a few times *c* for possible expansion velocities. These results are consistent with bulk relativistic core velocities, provided the source axes are near the plane of the sky.

Key words: quasars – VLBI

1. Introduction

Mapping the nuclear radio structure in extended lobe dominated extragalactic radio sources, associated with active galactic nuclei, is one of the most intriguing subjects in extragalactic VLBI investigations (see e.g., Kellermann and Pauliny-Toth, 1981). Following VLBI surveys by Schilizzi (1976) and Preuss et al. (1977) which demonstrated that many extended sources have compact radio cores on linear scales of 1 to 10 parsec in the nuclei of the associated optical object, a number of the more luminous cases have been mapped with intercontinental VLBI networks. These sources include the radio galaxies Cygnus A, 3C111, 3C390.3 and NGC315 (Kellermann et al., 1981; Preuss et al., 1980; Linfield 1981), Virgo A/M87 (Reid et al., 1982), NGC6251 (Readhead et al., 1979) and 3C236 (Barthel et al., 1985), as well as the quasars 3C309.1 (Kus et al., 1981) and 3C179 (Porcas, 1984). Since the radiative lifetime in these compact cores are roughly five orders of magnitude smaller than the lifetimes in the larger scale radio emission, important conclusions on the evolution of the radio source morphology can be drawn. By making VLBI maps at pc-scale resolution with regular time intervals, one may furthermore hope to obtain information on the evolution of the radio core itself.

Because of their relative faintness, as yet few radio cores in extended quasars have been studied in detail. Nevertheless, many quasar radio cores can be mapped, provided sensitive VLBI networks are used. We are carrying out such a project, the first results of which have been reported by Barthel et al. (1984 – BMSP hereafter). In addition to studying the evolution of extended sources in general and of the cores in particular, this project is aimed at relating the statistics of the core sizes to other source parameters such as radio, optical and X-ray luminosities, optical polarization, emission line widths etc. in order to provide clues as to the nature of active galactic nuclei. We are also undertaking multi-epoch observations of the core structures to test the different models explaining superluminal motion.

In BMSP we presented the results of a pilot survey for compact radio cores in a complete sample consisting of sixteen quasi-stellar radio sources having (i) $\delta_{1950} > 0°$, (ii) known extended radio structure and redshift, and (iii) 5 GHz core flux density exceeding 100 mJy. Our high detection rate implies linear sizes $\lesssim 10$ parsec for these cores, and in some cases our data suggests multiple component structure with separations of about 10 parsec (projected on the overall source axis). In this second paper we present and discuss radio maps at milliarcsec resolution of a subset of the original sample, made at two epochs, separated by one year.

2. Observations and data reduction

As in the zero-epoch (1981.3) pilot survey observations, the observing frequency was 4990 MHz, and the data were recorded using the standard MkIIC VLBI system (Clark, 1973). The measured sense of polarization was LCP. First epoch observations of a subset of four quasar cores were carried out on April 5–6–7, 1982, using a five telescope transatlantic VLBI network. Parameters of the interferometer array are given in Table 1. Table 2 lists the quasars observed, which were selected from the original source sample on the basis of milliarcsecond scale structure in their cores (see BMSP).

From Table 2 it can be seen that the overall dimensions of the extended double lobed radio structures are large. Indeed, 1721 + 343 is the largest quasar known (Jägers et al., 1982). Core flux density variability has been reported in 1721 + 343 and probably in 0742 + 318 (BMSP).

The quasars 0610 + 260 and 0742 + 318 were observed in source switching mode, over a period of about 7 hours, while the quasar 1137 + 660 was observed for a period of ~10 hours. Finally, the

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Table 1. Parameters of the interferometer arrays, at λ6 cm. The numbers in brackets refer to changes during the second epoch (1983.3) observations

Telescope location	Diameter (m)	T_{sys} (K)	Antenna sensitivity (K/Jy)
Effelsberg, FRG	100	65	1.40(1.29)
Onsala, Sweden	25	40	0.06
Green Bank, USA	43	42	0.28
Socorro, USA	130	50	2.2
Owens Valley, USA	40	115(88)	0.21(0.26)

quasar 1721+343 was observed for a period of ~9 hours, but not by the VLA. Cross correlation of the data was carried out at the Max-Planck-Institut für Radioastronomie, Bonn, FRG. The coherently averaged correlation coefficients were calibrated according to the precepts of Cohen et al. (1975), assuming the primary calibrator 0235+164 to be unresolved on the intra-European and intra-USA baselines. Corrections were applied for coherence losses caused by the somewhat long integration time of 6 min.

The observing conditions during the first epoch were not ideal. High winds at the VLA and hardware problems at Onsala and Green Bank, as well as the source switching on 0610+260 and 0742+318 resulted in *u–v* coverages that were far from complete for all the four sources, with the result that we were not able to produce reliable hybrid maps of the radio cores. Particularly, the core emission in 1137+660 is weak: correlated flux densities between 100 and 200 mJy were found. Much phase noise was present and this source was not always detected on the weaker baselines. We were therefore only able to produce a crude model for this core. Clearly, the more sensitive Mark III equipment is required to map this compact component, and this has been done by Zensus et al. (1984). The multiple component structure as suggested from the few *u–v* points in the zero-epoch observations (BMSP) for 0742+318 and 1721+343 appeared to be present indeed. Moreover, comparison of the *u–v* data points (epochs 1981.3 and 1982.3) showed that the two epoch data sets were not inconsistent with possible expansion in the radio cores. Therefore, second epoch observations of the (brightest) cores 0610+260, 0742+318 and 1721+343 were made to search for possible expansions, using the same five-station transatlantic VLBI network, exactly one year after the first epoch. See Table 1 for the telescope parameters (changes are noted in brackets).

The observing times were about 9 hours for 0610+260 and 0742+318 (continuous tracks this time), and about 12 hours for 1721+343, the common visibility in Europe and the USA being somewhat less of course. These second epoch data were correlated on the CIT/JPL correlator at the California Institute of Technology, Pasadena, USA. The correlation coefficients, coherently averaged for 6 min, were calibrated following Cohen et al. (1975). Although we did not obtain fringes on baselines to Onsala, the remaining four telescopes provided us with sufficient, good data, in order to produce reliable radio maps, for which we used the CIT VLBI iterative mapping algorithms.

3. Results and discussion

The results of this study are twofold. First, maps of three radio cores at two milliarcsecond resolution have been obtained (epoch 1983.3), having a dynamic range of about 10:1. The properties of the parsec scale core structures revealed in these maps are discussed below in Sects. 3.1 and 3.2. Second, comparison of the two epoch data, separated by a one year interval allows a first study of the evolution, or the lack of it, in the parsec scale radio morphology in the cores of these large extragalactic radio sources. This is discussed in Sect. 3.3.

3.1. Alignment of the large and small scale structure

The model we derive for the core in 1137+660 at epoch 1982.3 is a single gaussian component of 0.8 × 0.5 milliarcsec (FWHM) in p.a. 110°, which has a flux density of 200 mJy. This model provides a reasonable fit to the translantic baseline data. The behaviour of the visibility on the short Effelsberg-Onsala baseline indicates the presence of some additional larger scale structure. Location of this additional structure was impossible. The position angle of the small structure is in good agreement with that of the large scale (Table 2). The final maps obtained for the cores in 0610+260, 0742+318, and 1721+343 from the second epoch data (1983.3) are shown in Figs. 1–3. A circular restoring beam of 2 milliarcsec was used in all cases. As the core in 0610+260 is rather weak, the noise level is about five per cent of the peak flux density in the map. The linear sizes involved are indicated in the maps. These maps should be compared with the maps of the overall radio structure, the references to which are given in Table 2. For easy comparison we have listed the overall source position angles in Table 2. Composite maps of 0742+318 and 1721+343 are shown in Fig. 4.

These four sources add to the sample of very large extended radio sources in which the small scale core radio structure appears

Table 2. The observed sources, with references to structure information

Quasar	Other name	Redshift	Proj. lin. size[a] (kpc)	Large scale p.a.	Core/overall 5 GHz flux density	References
0610+260	3C154	0.580	250	101°(E), −87°(W)	600/1800	1, 6
0742+318	4C31.30	0.462	530	128°(E), −57°(W)	750/850	1, 3, 4
1137+660	3C263	0.652	240	111°	200/1100	1, 5
1721+343	4C34.47	0.206	1270	−17°	375/800	1, 2

References: 1. BMSP; 2. Jägers et al. (1982); 3. Neff (1982); 4. Neff and Brown (1984); 5. Pooley and Henbest (1974); 6. Riley and Pooley (1975)

[a] $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$

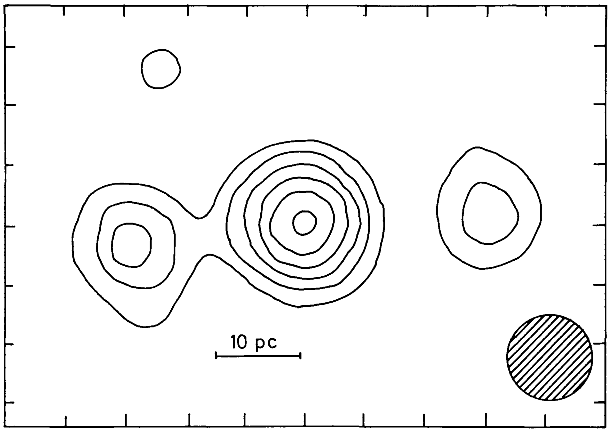

Fig. 1. 0610 + 260 core. Restoring beam is 2 mas; contour levels are 10, 20, 30, 50, 70, 95 % of peak brightness, which is 63 mJy/beam; tick interval is 1.4 mas; linear scale is indicated

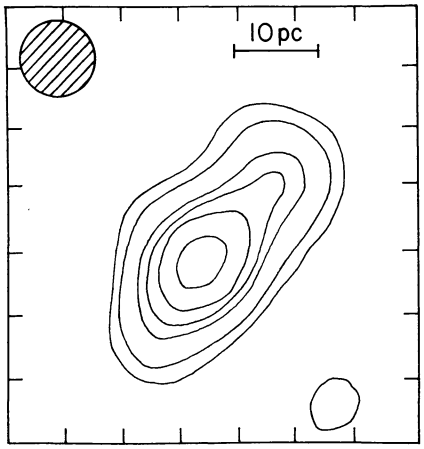

Fig. 2. 0742 + 318 core. Restoring beam is 2 mas; contour levels are 5, 10, 25, 35, 50, 80 % of peak brightness, which is 106 mJy/beam; tick interval is 1.6 mas; linear scale is indicated

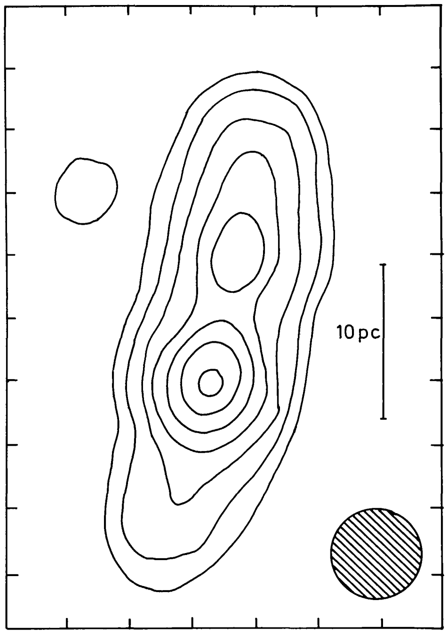

Fig. 3. 1721 + 343 core. Restoring beam is 2 mas; contour levels are 5, 10, 20, 35, 50, 70, 95 % of peak brightness, which is 100 mJy/beam; tick interval is 1.4 mas; linear scale is indicated

to be aligned (to within 15°) with the large scale morphology. Kellermann and Pauliny-Toth (1981) discuss other examples. Except for 1137+660 (crude model), this alignment is certainly not perfect. Particularly interesting in this respect are 0610+260 and 0742+318. For the former, the position angles of the two features at distances of ~ 35 pc east and west of the (assumed) core (Fig. 1) are 98° and $-87°$, which are very similar to the position angles of the radio lobes, at distances of ~ 100 kpc from the core (Table 2). This may indicate that (i) the apparent large scale position angle asymmetry has origin deep inside the core, and (ii) this asymmetric core behaviour is long-lasting (see also Barthel et al., 1985). For 0742+318, jet bending on the 100 kpc scale has been reported by Neff (1982) and Neff and Brown (1984). The fact that the VLBI position angle lies within the cone defined by the large scale bending (see map in Neff, 1982), argues for an intrinsic origin for this bending, i.e., precession of the source axis. In 1721+343 the difference in large and small scale position angle is $\sim 5°$.

3.2. Two-sided nuclear jets

Inspection of the maps shows emission on both sides of the nucleus, assuming that the actual core in the quasars coincides with the peak in the radio maps. To test this assumption, we intend to make maps at higher frequency, thereby possibly locating the actual flat spectrum core component. We have checked the reliability of the two-sided emission by cleaning the dirty maps in different windows at various positions with respect to the assumed core, and subsequently examining the residuals, and are confident that all the features in our maps are real, particularly for 0742+318 and 1721+343 where the fit with the observed (closure) amplitudes and closure phases is very good. The apparent lack of two-sided cores in many other sources has been explained as being due to Doppler beaming: plasma clouds emitting synchrotron radiation will appear brightened by large factors when approaching the observer with bulk relativistic velocities and similarly weakened when receding. An intrinsic two-sided core inclined at an angle smaller than 90° to the line of sight will appear one-sided, since, at limited dynamic range, we only observe the approaching side, provided bulk relativistic velocities are involved (see e.g., Kellermann and Pauliny-Toth, 1981). However, Linfield (1982) concluded that the observed parsec scale asymmetry in the cores of several large double radio galaxies is source intrinsic. For example, the agreement between the projected position angles of the optical rotation axis (Simkin, 1977) and radio axis (Hargrave and Ryle, 1974) in Cyg A, the former being inclined at $83° \pm 3°$, suggests that the radio source lies roughly in the plane of the sky. The high dynamic range VLA maps of Cyg A (Perley et al., 1984) show the ghost of a counterjet on the large scale, confirming that Cyg A is likely to be in the plane of the sky. Nevertheless, the small scale core structure in Cyg A is one-sided with brightness ratio > 15 (Linfield, 1981). Since the observed brightness ratios generally exceed 10, spectral effects as cause for the one-sidedness are unlikely.

Bridle (1984) has shown empirically that in radio sources having intrinsic luminosity at 1.4 GHz $P_{1.4} > 10^{24.5}$ W Hz^{-1} ($H_0 = 100$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$) the kpc-scale jets are one-sided, whereas for sources with $P_{1.4} < 10^{24.5}$ W Hz^{-1} the large scale jets are found to be two-sided. We note that the three quasars discussed here exceed this power by one (1721+343), two (0742+318), and three (0610+260) orders of magnitude.

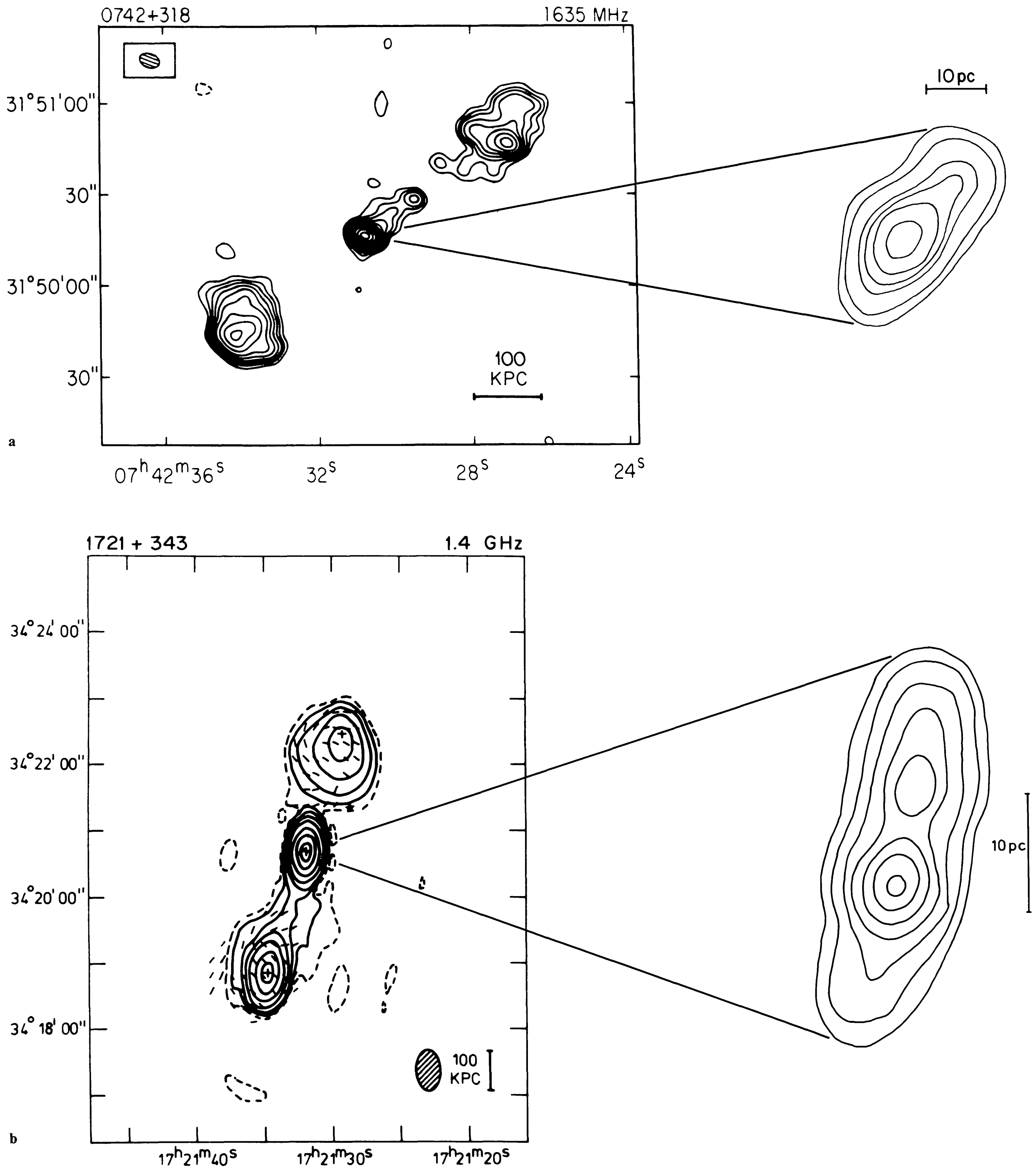

Fig. 4a and b. The figure shows the alignment of the core relative to the overall quasar morphology, for **a** 0742+318 and **b** 1721+343 respectively. Linear scales are indicated. The large scale maps are reproduced with kind permission of S.G. Neff (0742+318) and W.J. Jägers (1721+343)

3.3. Orienation to the line-of-sight and expansion velocities

We suggest that the two-sidedness observed in our sources is consistent with either non-relativistic bulk velocities in the cores (no beaming), or large inclinations of the source axes to the line-of-sight. Quantitatively, adopting $\beta \equiv v/c = 0.98$ in the cores ($\gamma = 5$), the constraint on the flux density ratio on both sides of the core (observed to be less than ~ 3), becomes

$$\left(\frac{1-\beta\cos\theta}{1+\beta\cos\theta}\right)^{-3} \leqq 3$$

assuming $\alpha_{\mathrm{core}} = 0$ and using the flux density ratio expression for continuous core emission (Scheuer and Readhead, 1979). We derive a value for $\theta > 79°$. Allowing $\gamma = 2 (\beta = 0.87)$ the constraint becomes $\theta > 78°$. If $\theta = 60°$, the constraint on γ becomes $\gamma < 1.07$ (or $\beta < 0.36$). The evidence from superluminal motion for the existence of relativistic core velocities (see e.g., Marscher and Scott, 1980) is compelling, but such velocities are only allowed in the cores of the extended quasars considered here provided the sources are within 12° of the plane of the sky. Since the sources involved have very large projected dimensions and are therefore expected to be oriented close to the plane of the sky, this constraint is not unreasonable. Recently, Kapahi and Saikia (1982) have reported an anticorrelation between the projected linear size and the fractional core flux density in extended triple sources, which they subsequently attributed to relativistic Doppler beaming. The very large quasars discussed in the present paper do not support this correlation since the cores are relatively bright (Table 2) and beaming cannot be an important factor. An intrinsic origin has to be invoked for their high core brightness. To examine the possibility of superluminal motions in our sources, we made a comparison of the second epoch data with the first epoch data, as follows. We superimposed the calculated visibility amplitudes of the 1983.3 models on the visibility amplitudes observed during the first, 1982.3 epoch, and compared the positions of the maxima and minima of the two data sets. The closure phase data from the first epoch had low quality, and were not useful for this comparison.

Apart from some scaling deviations due to calibration uncertainties, no difference in the visibilities from the two epochs was found within the errors, on the baselines in common. Since our data points correspond to 6 min averages, however, the uncertainties are not negligible. Comparing the long, transatlantic baseline data we were only able to derive upper limits to possible proper motion in the cores of 0742+318 and 1721+343 of $\mu < 0.15$ milliarcsec per year. The first epoch data on 0610+260 are not of sufficient quality to make this comparison. The observed constraint on μ converts to $\beta_{\mathrm{app}} < 3.3$ and $\beta_{\mathrm{app}} < 1.7$ for possible superluminal motion in 0742+318 and 1721+343, respectively, using $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.5$. For the standard cosmology in the superluminal literature ($H_0 = 55\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ and $q_0 = 0.05$), the limits on β_{app} are 5.0 and 2.4 for the two sources respectively. The lowest upper limit to possible superluminal expansion (for 1721+343) is interesting. Using the well-known expression for apparent superluminal motion caused by bulk relativistic motion near the line-of-sight (e.g., Kellermann and Pauliny-Toth, 1981),

$$\beta_{\mathrm{app}} = \frac{\beta\sin\theta}{1-\beta\cos\theta},$$

with θ the inclination of the source axis to the line of sight, the upper limit to β_{app} of 1.7 converts to $\beta < 0.87$ for $\theta = 40°$. This indicates that bulk relativistic core velocities ($\gamma > 2$) are consistent with our data, provided the radio source is within 50° of the sky plane. This weak constraint is in agreement with the constraint derived from the observed two-sidedness, as expected. It will be clear that determination of a small β_{app}-value by making third epoch observations would be most useful in putting constraints on the actual velocities, β, involved.

4. Conclusions

The data obtained provide another four examples of good alignment of the parsec scale core structure with the 100 kpc scale overall morphology in large, extended extragalactic radio sources.

Although Doppler beaming may play a role, the observations also require an intrinsic origin for the observed core morphology and brightness. This conclusion depends critically on the assumed identification of the brightest core component in our maps with the actual core, and needs further investigation.

We do not see any convincing evidence for superluminal motion in the two sources where a comparison can be made at two epochs. Our upper limits of a few times c are consistent with bulk relativistic motion ($\gamma > 2$) at angles $\theta > 40°$ to the line-of-sight. Third epoch observations should serve to refine this result further.

Acknowledgements. We thank the European and the US VLBI networks for supporting the observations at the radio telescopes, and the VLBI staffs at the Max-Planck-Institut für Radioastronomie and the California Institute of Technology for help with the data processing. The assistance of Dr. T.J. Cornwell in obtaining the VLA data is also gratefully acknowledged.

PDB acknowledges support by the Netherlands Organization for the Advancement of Pure Research (ZWO), through ASTRON grant 19–23–13, and also acknowledges travel support from the Leids Kerkhoven–Bosscha Fonds.

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